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The increase of soil organic carbon as proposed by the "4/1000 initiative" is strongly limited by the status of soil development - A case study along a substrate age gradient in Central Europe

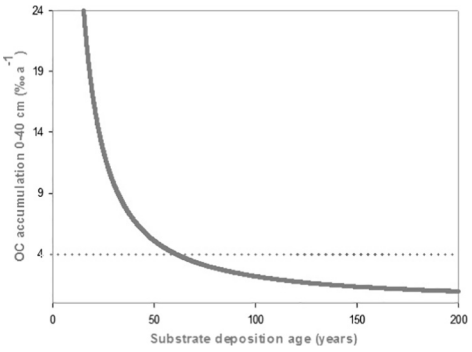
Jasmin Schiefer [a], Georg J. Lair [a,*], Christopher Lüthgens [b], Eva Maria Wild [c], Peter Steier [c], Winfried E.H. Blum [a]

[a] Institute of Soil Research, University of Natural Resources and Life Sciences, Peter-Jordan-Str. 82, 1190 Vienna, Austria
[b] Institute of Applied Geology, University of Natural Resources and Life Sciences, Peter-Jordan-Str. 82, 1190 Vienna, Austria
[c] University of Vienna, Faculty of Physics, Isotope Research and Nuclear Physics, Vienna Environmental Research Accelerator, Währinger Str. 17, 1090 Vienna, Austria

HIGHLIGHTS

- The status of soil development strongly influences the C-accumulation rates in soils.
- After 350 years of soil development, C-sequestration under various land use is highly limited in our study area.
- C-accumulation of more than 4‰ per year was only observed during the first 60 years of soil formation.

GRAPHICAL ABSTRACT



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ABSTRACT

During COP 21 in Paris 2015, several states and organizations agreed on the "4/1000" initiative for food security and climate. This initiative aims to increase world's soil organic carbon (SOC) stocks by 4‰ annually. The influence of soil development status on SOC dynamics is very important but usually not considered in studies. We analyse SOC accumulation under forest, grassland and cropping systems along a soil age gradient (10–17,000 years) to show the influence of soil development status on SOC increase.

SOC stocks (0–40 cm) and accumulation rates along a chronosequence in alluvial soils of the Danube River in the Marchfeld (eastern Austria) were analysed. The analysed Fluvisols and Chernozems have been used as forest, grassland and cropland for decades or hundreds of years.

The results showed that there is a fast build-up of OC stocks (0–40 cm) in young soils with accumulation of ~1.3 t ha^{-1} a^{-1} OC in the first 100 years and ~0.5 t ha^{-1} a^{-1} OC between 100 and 350 years almost independent of land use. Chernozems with a sediment deposition age older than 5.000 years have an accumulation rate < 0.01 t OC ha^{-1} a^{-1} (0–40 cm).

Radiocarbon dating showed that the topsoil (0–10 cm) consists mainly of ">modern" and "modern" carbon indicating a fast carbon cycling. Carbon in subsoil is less exposed to decomposition and OC can be stored at long-time scales in the subsoil (^{14}C age of 3670 ± 35 BP).

In view of the '4/1000' initiative, soils with constant carbon input (forest & grassland) fulfil the intended 4‰ growth rate of SOC stocks only in the first 60 years of soil development. We proclaim that under the present climate in Central Europe, the increase of SOC stocks in soil is strongly affected by the state of soil development.

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* Corresponding author.
E-mail address: georg.lair@tirol.gv.at (G.J. Lair).

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1. Introduction

Soil and its organic carbon (OC) content play an important role for food security, in the global carbon cycle and in climate change. Worldwide, soils are the largest terrestrial pool of organic carbon and store about 2500 Pg of C to 2 m depth in the form of soil organic matter (SOM) (Batjes, 1996; Scharlemann et al., 2014; Trumbore, 2009). Due to land use and land cover changes, emissions from terrestrial ecosystems are the second largest anthropogenic source of carbon into the atmosphere (Scharlemann et al., 2014). The loss of SOC from agricultural land is identified as one of the eight major threats to soils (Blum, 2013) as it negatively influences soil fertility and the soil's function of providing ecosystem services (Haddaway et al., 2016). In Europe, a too low SOC content (<1%) in agricultural soil is also one of the most limiting factors for soils to be resilient against negative environmental impacts and to perform on high levels (Schiefer et al., 2016). Such a high resilience and production capacity of soils is the basis for a sustainable intensification as it allows intensive agriculture with high yields but without the massive negative environmental impacts (Buckwell et al., 2014; Schiefer et al., 2015).

The importance of SOC for food security and climate change was also recognised during the United Nations Framework Convention on Climate Change, 21st Conference of the Parties (COP 21) launched in Paris, France, in December 2015. At COP 21 the "4 per mille - Soils for food security and climate" initiative was introduced. This "4 per mille" or "4/1000" initiative seeks to increase global soil carbon in the first 40 cm of agricultural soils by 4‰ annually in the next 25 years (Lal, 2016; Rhodes, 2015). This increase could compensate for the global greenhouse gas emissions and resultant climate change, ensure food security and contribute to the UN sustainable development goals (4pour1000, 2017). To reach this ambitious goal, management strategies such as conservation agriculture, mulch farming, cover cropping, agroforestry, biochar application, improved grazing and/or restoration of degraded soils were suggested (Lal, 2016). However, some studies suggest that a change of management practice cannot prevent ongoing losses of SOC from the topsoil (Steinmann et al., 2016).

For the "4 per 1000" initiative it is also important to maximize the residence time of additional C in soils (Dignac et al., 2017) and to define C saturation levels to identify realisable C-accumulation potentials (Minasny et al., 2017). Studies showed that soils can reach a maximal soil C level showing no response to increasing C inputs due to a carbon saturation in soil (Gulde et al., 2008; Six et al., 2002; Stewart et al., 2008, 2007; West and Six, 2007; Zehetner et al., 2009). Besides the finite capacity of soils to store OC, it must also be considered that the process of carbon storage is reversible (Powlson et al., 2011). Zehetner et al. (2009) showed that along the floodplain soil chronosequence in the Marchfeld, carbon is rapidly accumulated in the first years of soil development and shows equilibrium and stabilization in various humus fractions already within 100 years. Another study showed that a recently developed Mollisol shows a positive non-linear relation between C inputs and SOC stocks. However, the same management does not cause any OC stock increase in mature Mollisols (You et al., 2017).

As a consequence, the main objective of this study is to analyse the influence of the soil development status on the accumulation potential of SOC. To our knowledge, we evaluate the first time for how many years soils show a C-accumulation potential of (more than) 4‰ per year under the actual land use and management practices.

In the Marchfeld region (eastern Austria) soils along a substrate age gradient developed on the same parent material and under the same climate (Zehetner et al., 2009). The soil chronosequence includes the whole Holocene and a maximum sediment deposition age of 17,000 years, whilst the youngest soils have only recently developed on fresh river sediments (<40 years). We analysed the carbon stocks and accumulation rates in the upper 40 cm as proposed by the '4/1000' initiative and performed radiocarbon dating for a better understanding of OC dynamics along the soil chronosequence.

2. Material and methods

2.1. Study area and soil sampling

The study area is located in the Marchfeld, a Danube floodplain downstream of Vienna/Austria (Fig. 1) showing little variation in topography and climate. More information and a detailed description of the study area can be found in Lair et al. (2009a, 2009b, 2009c) and Zehetner et al. (2009). The area is located in a continental climate with a mean annual temperature of ~9 °C and a mean annual precipitation of about 550 mm in the past 30 years. The Marchfeld is situated in the tectonically active Vienna Basin. The formation of the Vienna basin terrace staircase has been controversially discussed, especially with regard to the role of climatic vs. tectonic forcing factors. An overview about this discussion was recently provided by Lüthgens et al. (2017). The study area is strongly influenced by the Danube River which was regulated from 1870 to 1875. From 1882 to 1905 a flood control dike was built (Fig. 1) which disconnects the older part of the floodplain from the Danube River. The land close to the river experiences regular floods. The selected sites (except islands) are located close to the dike, which are only slightly affected by inundations and accompanied sediment input. We analysed soils under conventional agricultural use as well as under semi-natural forest and grassland (mowed once or a year).

The history of land use in the Marchfeld area can be exactly retraced till the late 18th century (Hartmann, 2003). However, the first settlement in this area was very sparse in the Neolithic period. Since the Copper Age a more or less dense population on higher elevations on the border to the Marchfeld can be retraced and since the Middle Ages settlements and agricultural production is documented (pers. comm. University Vienna, Institute of History).

The soil sampling campaigns took place between 2010 and 2014. Soil samples were carefully chosen based on aerial photographs and landscape evaluation. Each study site (Fig. 1) was sampled at least in triplicates at the corners of an equilateral triangle of 10 to 20 m. A fixed-depth interval sampling method (using an 8-cm core drill with a core height of 15 cm from Eijkelkamp Agrisearch Equipment) was combined with a horizontal sampling method (in soil pits) down to a soil depth of 60 to 100 cm, depending on the depth of the AC-horizon.

Soils close to the Danube River experience dynamic conditions that could result in eroded soil profiles. Therefore, all soil profiles were carefully analysed in the field. Soil samples were only taken from profiles with clearly distinguishable A, AC and C horizons and without considerable changes in soil textures.

2.2. Soil characteristics and soil age

All analysed soils developed on Danube sediments of the same parent material. The mineralogy of the river sediments consists of quartz (~35%), calcite and dolomite (~26%), chlorites (5%), Illites/Muscovites (15%), Feldspar (~15%) and Smectites/Vermiculites (~1%). Clay minerals show no transformation along the chronosequence, which can be explained by the carbonate buffered soil system. Regularly floods lead to a deposition of predominantly silt- and fine sand-sized particles at sites within the dike. However, these deposition rates are on average below 0.1 mm per year in the last ten years (pers. Communication, National Park "Donau-Auen"). Older soils outside the dike have a finer texture mainly categorised as loamy silt (Zehetner et al., 2009). The young soils are classified as Fluvisols (within the dike) and show a progressing development to Chernozems with increasing soil age and distance from the Danube.

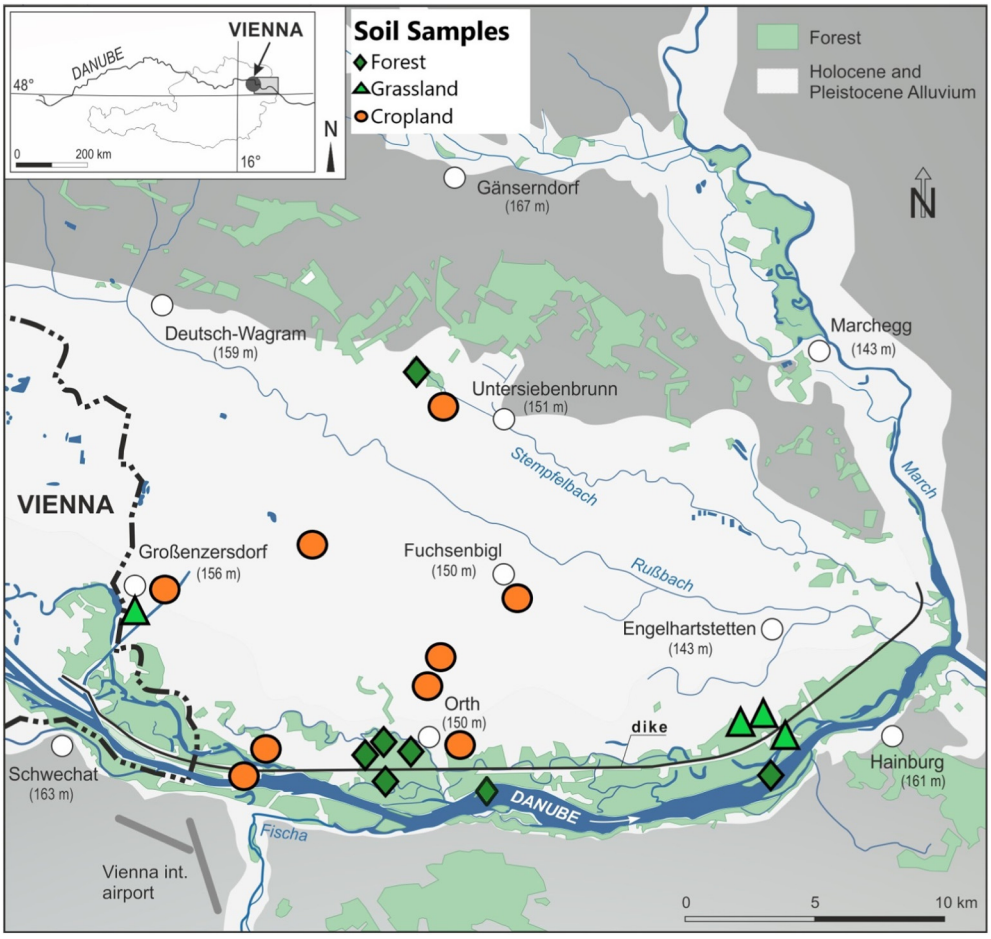

Fig. 1. Study area and sampling spots of the Danube floodplain in the Marchfeld, east of Vienna/Austria.

Soil pH is slightly alkaline across the whole chronosequence (pH: 7.6–8.0 in 0–10 cm). With increasing soil age, carbonate contents in the subsoil strongly increases (from ~20% to ~45%) reflected by increasing soil pH (from ~7.6 to ~8.6).

The age of individual soil layers was determined by ^{137}Cs to assess short-term sedimentation and soil development at decadal time scales. The ratio of oxalate- to dithionite-extractable iron (Fe_o/Fe_d) (degree of iron oxide crystallinity) was additionally used for soils with sediment deposition ages of 100–2.000 years. A detailed description of the analysis can be found in Lair et al. (2009a).

Optically stimulated luminescence (OSL) dating was used to determine the ages of sediment deposits from the beginning of the Holocene until the 18th century (Fiebig et al., 2009; Georg J. Lair et al., 2009a). A detailed explanation of the analysis can be found in "supplementary Information".

2.2.1. Radiocarbon dating

Radiocarbon determinations in organic matter of bulk soil samples were performed at the VERA Laboratory (Vienna Environmental Research Accelerator). The soil samples were ground and homogenized. The amount of CaCO3 and the total amount of organic carbon present in the sample were determined in subsamples of the soils (see below).

For ^{14}C sample preparation the required sample amount was estimated from the OC determinations. The ^{14}C samples were pretreated with 1 M HCl at 60 °C, after 1 h the HCl was renewed and the treatment continued for another 1 h in order to remove $CaCO_3$. Subsequently the samples were washed to near neutral pH, centrifuged and dried. Details about further sample processing and ^{14}C measurement with accelerator mass spectrometry (AMS) are given e.g. in Wild et al. (2008) and Steier et al. (2004), respectively.

2.2.2. Determination of organic carbon

Total organic carbon contents were quantified by dry combustion using an elemental analyser (Carlo Erba, Milano). The organic carbon (OC) content was calculated as the difference of total and inorganic carbon (carbonate) content. The carbonate content was quantified gas-volumetrically by measuring the volumetric release of CO_2 after adding 10% HCl to the soil in a calcimeter. The accumulation rates were calculated with organic carbon contents corrected by the OC input along with the river sediments. Measurements of sediments showed that carbon contents of the sediments are on average 7 g kg^{-1} (see Zehetner et al., 2009).

3. Results

3.1. Development of the soil layer containing humified organic matter

The A-horizon in soils presents the soil layer where organic matter is accumulating with time and its velocity of build-up reflects the formation rate of "living" soil. Along with soil age the depths of the A-horizons increases logarithmically ($R^2 = 0.9947$) as can be seen in Fig. 2. At the beginning of soil formation, the A-horizon increases up to 3 mm per year. This development is usually highly dynamic and is certainly also influenced by the Danube River (e.g. nutrient and water supply for fast pioneer-plant growth; Zehetner et al., 2009). After ~350 years of soil development, the soil formation rate is decreasing to ~1.0 mm per year. Older soils reach a formation rate <0.1 mm per year. The A-

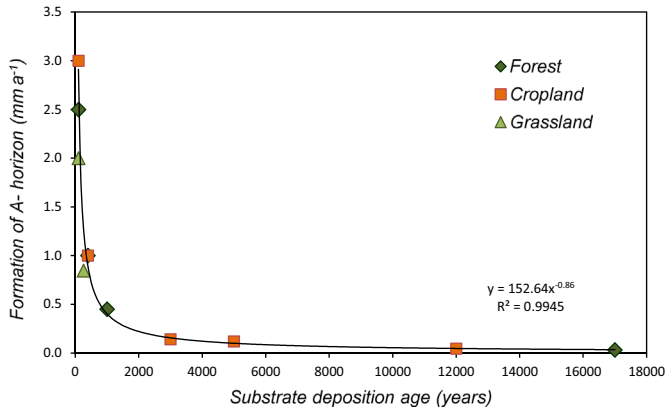

Fig. 2. Development of the A-horizon (mm a^{-1}) along the studied soil chronosequence in the Marchfeld. The growth rate of the A-horizon was calculated by its depth divided by the soil age.

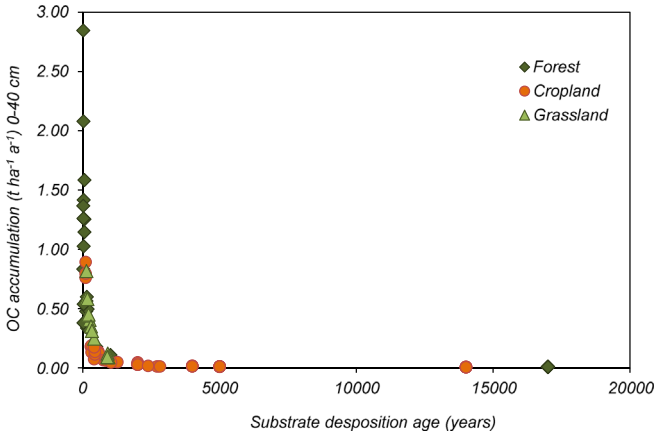

Fig. 4. Soil organic carbon accumulation rates (t ha^{-1} a^{-1}) in the topsoil (0–40 cm) under different land uses along a chronosequence in the Marchfeld.

horizons at the oldest sites with a sediment deposition age of maximum 17,000 years covering the whole soil formation in the Holocene, increase nowadays only 0.03 mm a^{-1} and reach a soil depth of 60 cm. Older soils or naturally evolved soils with a deeper A-horizon were not found in the Marchfeld.

3.2. Increase of SOC and stocks in time scale

Similar to the A-horizon development, the SOC contents and stocks change with time along the age sequence. Due to high organic matter inputs, forest sites rapidly build up to 50 t ha^{-1} in the soil profile (Fig. 3) within 30 years of soil development.

Soils with an age of ~100 years show an increase of OC stocks to ~100 t C ha^{-1} almost independently of land use.

OC-accumulation rates (Fig. 4) are decreasing after 100 years of soil development in soils under forest and grassland systems. After ~350 years, the OC increase flattens rapidly in the topsoil. The OC accumulation rates decrease to ~0.15 t C ha^{-1} a^{-1} in soils with an age between 500 and 1000 years in the first 40 cm and to ~0.08 t C ha^{-1} a^{-1} below 40 cm depth. The oldest forest site with a maximum sediment deposition age of 17,000 years accumulates only 0.01 t C ha^{-1} a^{-1} and reaches an OC stock up to 190 t C ha^{-1} (0–40 cm). These oldest sites also reach high OC stocks of ~95 t C ha^{-1} below 40 cm depth with accumulation rates of <0.01 t C ha^{-1} a^{-1}.

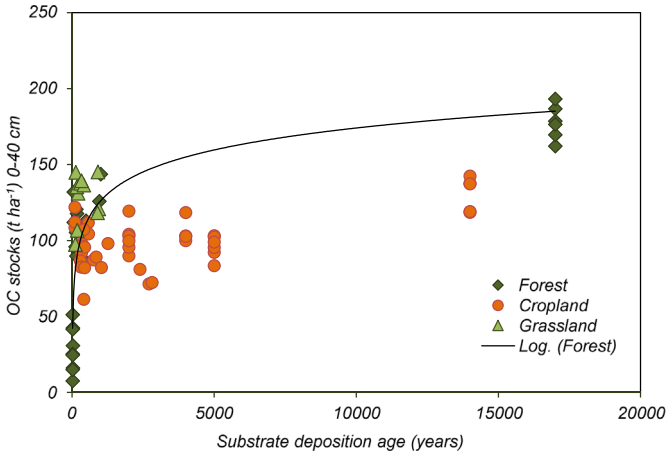

Fig. 3. OC stocks (t ha^{-1}; 0–40 cm) of Fluvisols and Chernozems under different land uses along a chronosequence in the Marchfeld.

OC stocks in the intensively managed cropland sites show no clear trend along the chronosequence (Fig. 3). The accumulation rate of cropland soils is similar compared to grassland and forest soils at soil ages of ~100 years (Fig. 4). At soil ages of >350 years cropland sites accumulate less OC compared to forest or grassland sites: Cropland sites accumulate on average 0.17 t ha^{-1} a^{-1} compared to grassland sites with an accumulation of 0.28 t ha^{-1} a^{-1} 0–40 cm. In soils with a sediment deposition age of ~1000 years (0–40 cm) cropland sites accumulate half the OC compared to semi-natural systems (cropland soils: 0.05 t ha^{-1} a^{-1} and grassland soils: 0.1 t ha^{-1} a^{-1}).

3.3. Mean residence time of accumulated SOM indicated by radiocarbon dating

Radiocarbon ages determined for SOM in the topsoil (0–10 cm) with substrate deposition age < 350 years are '>modern'; i.e. affected by the so called bomb peak from nuclear weapons testing. The pMC values show that the OC of the topsoil is composed of at least two fractions with different ^{14}C values, a young component originating from the ^{14}C bomb peak era and a component with lower pMC values which is a remnant of earlier deposited organic material.

The topsoil of the oldest forest site (maximum sediment deposition age of 17,000 years) yielded a 'modern' ^{14}C–age of 40 ± 40 years before present (BP). Again, the determined ^{14}C value is the result of the presence of a "fresh" OC component mixed with remnants of old organic material.

In general, ^{14}C values of the top soils seem to reflect a fast decomposition and mineralization of a considerable part of fresh SOM with the remaining material mixed with older SOM.

For the OC in the AC transition layers much older radiocarbon ages than for the topsoil were determined (Table 1). Radiocarbon ages can be older than soil ages due to the presence of old OC, which was co-deposited along with river sediments in early stages of floodplain creation. An average ^{14}C–age of ~450 years (BP) was obtained for the cropland and the forest site (350 years), showing that the organic carbon in the subsoils is less exposed to decomposition processes than in the topsoil. The AC layer of the grassland site with a soil age of 350 years has the youngest ^{14}C age compared to other land uses with same soil age. However, this site also has a shallower A-horizon compared to other sites with a similar soil development status.

The forest site with a maximum sediment deposition age of 17,000 years has a radiocarbon age in the AC-horizon of 1990 ± 35 years (BP) and the cropland soil (maximum age of 12,000 years) has an average ^{14}C–age of 3670 ± 35 (BP). The $\delta^{13}C$ showed no trend and ranged between −23.5 and −32.2‰.

Table 1
Radiocarbon age of different soils along the chronosequence in the topsoil (0–10 cm) and the subsoil (AC-horizon).

Lab number	Land use/depths (cm)	Estimated substrate deposition age (years)	$d^{13}C$[a,b] [‰]	^{14}C-content[a,c] [pMC]	^{14}C-age[a] [BP]	Calibrated OC date[d]
VERA-6012	Grassland 0–10 cm	350	−28.46 ± 0.81	104.78 ± 0.48	–	>modern
VERA-5893	Forest 0–10 cm	350	−32.2 ± 1.1	106.47 ± 0.39	–	>modern
VERA-5897	Forest 0–10 cm	17.000	−26.9 ± 3.8	99.48 ± 0.47	40 ± 40	modern
VERA-6013	Grassland 15–30 cm	350	−23.5 ± 1.2	98.89 ± 0.41	89 ± 34	modern
VERA-5892	Cropland 35–45 cm	350	−25.2 ± 0.9	94.55 ± 0.39	450 ± 35	1400 CE (93.9%) 1500 CE 1600 CE (1.5%) 1620 CE
VERA-5894	Forest 35–45 cm	350	−30.9 ± 1.2	94.37 ± 0.44	465 ± 35	1405 CE (95.4%) 1480 CE
VERA-5896	Cropland 50–60 cm	12.000	−30.0 ± 1.6	63.32 ± 0.29	3670 ± 35	2190 BCE (1.1%) 2180 BCE 2150 BCE (94.3%) 1940 BCE
VERA-5898	Forest 50–60 cm	17.000	−24.5 ± 0.9	78.06 ± 0.35	1990 ± 35	90 BCE (1.6%) 70 BCE 60 BCE (93.8%) 90 CE

[a] 1σ-uncertainty.
[b] $\delta^{13}C$-Werte determined with the AMS system.
[c] Percent modern carbon.
[d] Calculated with the INTCAL13 calibration curve and the calibration program OxCal, given time range corresponds to a 2σ-confidence level, probability of the individual time ranges given in brackets.

3.4. Soil organic carbon accumulation potential in the 0–40 cm topsoil in respect to the 4/1000 initiative

A logarithmic function ($y = 15.619; \ln(x) - 6.9928; R^2 = 0.7688$) was derived from measured OC stocks in the 0–40 cm topsoils along the chronosequence in grassland and forest sites similar to the accumulation of OC. This allows the calculation of the maximum annual increase of OC stocks. Based on this calculation, the accumulation of OC each year in forest and grassland systems in the Marchfeld is below 4‰ after only 59 years of soil development when the C stocks reach ~65 t OC ha^{-1} (Fig. 5, Table 2).

A clear trend of measured OC contents in croplands with soil age was not measured in the bulk soil. Their median OC stock along the whole chronosequence is ~100 t C ha^{-1} in the topsoil (0–40 cm). Considering this as initial C stock, even a conversion from cropland to a forest could not lead to an annual accumulation of >4‰ according to our logarithmic function.

Using the conversion factor of C:CO_2 of 3.67 reveals, that after 50 years the potential to retain CO_2 is below 1 t CO_2 ha^{-1} a^{-1}. Soils older than 300 years have a CO_2 storage capacity of <0.2 t CO_2 ha^{-1} a^{-1} (Table 2).

4. Discussion

4.1. Carbon stock build-up with time

Long term studies analysing SOC dynamics under forest and grassland systems over a time period of thousands of years is usually not possible. The chronosequence in the Danube floodplain in Austria (Marchfeld) used in this study offers the rare opportunity to analyse SOC build up along the Holocene under the influence of the soil development.

Due to methodological differences of soil age estimation a distinction between the average soil age and maximum sediment deposition age was necessary. The age of young soils was analysed with ^{137}Cs and/or Fe_o/Fe_d ratio for each soil horizon. An average soil age for each profile was calculated. However, the oldest soils had to be dated with OSL, which is only possible in the subsoil, without bioturbation and infiltration of fine soil from the topsoil. Therefore, we could determine only the maximum sediment deposition age and not the average soil age. We can assume that the topsoil is younger but still reaches an average soil age of several thousand years.

Soil formation and development are usually very slow and dependent on the factors climate, parent material, topography, biological activity and time, which influence the formation of the soils system (Jenny, 1994). These factors are linked to SOC accumulation and stabilization processes.

All analysed soil samples in this study developed on the same parent material with a similar mineralogy and topography. Soil mineralogy, especially clay minerals do not change remarkably along the chronosequence, because weathering is limited due to high soil pH (>7) along the chronosequence. This allows the assumption, that the only difference between the samples is the soil age (time) and the soil cover (land use). However, also climatic changes in the past 20,000 years occurred in the studied region, which may have affected total SOC stocks and possible "equilibrium" stages of soil development during the Holocene. Our results show, that most soil formation processes and the potential to increase the OC stocks are finished after ~100 years of soil development due to the dynamics of organic material and the continental climate.

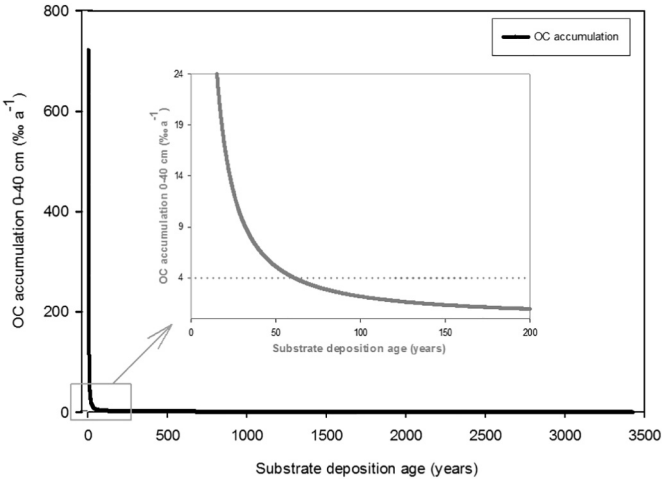

Fig. 5. Yearly increase of OC (‰) – The increase was calculated with logarithmic function based on measured values. The grey box shows at which OC stocks soils in the Marchfeld could contribute to the 4‰ initiative (below dotted line).

Table 2
Calculated soil organic carbon stocks, accumulation rates and CO_2 storage potentials along the chronosequence (0–40 cm) in semi-natural systems (forest and grassland). Based on measured values a logarithmic function was used for calculations.

Soil age	OC stock	OC accumulation	OC accumulation	CO_2 storage	CO_2 accumulation
(years)	(t ha^{-1})	(t ha^{-1} a^{-1})	(‰ a^{-1})	(t ha^{-1})	(t ha^{-1} a^{-1})
10	37.06	1.56	42.14	135.76	5.72
20	48.22	0.78	16.20	176.63	2.86
35	57.23	0.45	7.80	209.62	1.63
50	62.97	0.31	4.96	230.65	1.14
59	65.63	0.26	**4.03**	240.41	0.97
60	65.90	0.26	**3.95**	241.40	0.95
100	74.12	0.16	2.11	271.52	0.57
300	91.81	0.05	0.57	336.29	0.19
1000	111.19	0.02	0.14	407.28	0.06
3000	128.87	0.01	0.04	472.05	0.02

This shows that the analysed soils have developed 'equilibrium' under certain conditions. Such kind of "steady state" condition occurs, when inputs of matter (e.g. OC) to the systems are ongoing but losses via decomposition decreases any accumulation of OC in the soil over medium to long timescales (Schaetzl and Anderson, 2005). The reached 'steady state' conditions of soil moisture, gas exchange, freezing and soil biota could also explain why no AC-horizons (transition zone between the A-horizon and the C-horizon) can be found in deeper depths than 60 cm.

Once the soil status reached this 'steady state' condition, also no more substantial increases of OC occurred in the analysed soils (Figs. 3 & 4). The results suggests that the maximum carbon stabilization capacity (Beare et al., 2014) is reached after 100–350 years. At this stage, it seems that mineral surfaces are C saturated and the soil carbon stock has reached its maximum carrying capacity for storing soil carbon inputs (Six et al., 2002; Stewart et al., 2007).

Although we concluded that the soils reached a steady state after 100–350 years of soil development, an accumulation of OC was still detected. In the study area, chemical weathering processes of minerals were extremely slow, which also means, that no further adsorption sites for OC were created. We assume that minerals are not covered by a monolayer of C-loading (Beare et al., 2014; Mayer, 1994) but are rather adsorbing OM as patches (Chenu and Plante, 2006; Vogel et al., 2014). Chenu and Plante (2006) suggest that the gained clay sized fraction mainly contains nanometer- to micrometer sized micro-aggregates in which SOM is encrusted by minerals or coated minerals (Chenu and Plante, 2006). Additional OM preferentially binds to existing patches and not to free mineral surfaces (Vogel et al., 2014). OM also adsorbs to the Fe-(hydr)oxides in the form of a multilayer due to hydrophobic interaction between various organic compounds (Regelink et al., 2015).

For climate change mitigation measures, the stability of OC defined by its degradation rates is of equal importance to the actual OC content. According to its degradation rates, SOM can be divided into an active/labile pool (turnover times < 10 years), intermediate pool (turnover times between 10 and 100 years-highly influenced by soil management practices) and passive/stable pools (turnover times up to thousands of years - responsible for long term storage of SOM) (von Lützow et al., 2008).

The former assumption of chemical resistant material causing organic carbon structures with turnover times of thousands of years (stable pool) was shown to be of minor or no importance (Lehmann et al., 2008; Schmidt et al., 2011); especially the microbial accessibility (physical stabilization mechanisms) controls long-term carbon stability in soils (Blum et al., 2015; Lehmann and Kleber, 2015; Schmidt et al., 2011).

In our study, we link long-term stable carbon with high radiocarbon ages. The results suggest that in the topsoil, radiocarbon age is always >modern or modern independent of the soil age (Table 1). Our data seem to indicate that the majority of the organic matter is labile and almost completely turned over within a few decades. Such high dynamics in our study area have been shown by a previous study. A radiocarbon study by Stemmer et al. (2000) showed that >90% of added carbon is mineralized within 40 years under different management systems (crop rotation, spring wheat) in a long term field trial in the Marchfeld area.

The subsoil shows a different system compared to the topsoil as the AC-horizon is not affected by land management and receives its carbon mainly from roots and earthworms. The older OC in the subsoil can be explained by the limited input of fresh organic material and by a stabilization interaction with the minerals where the mineral surfaces have not yet been saturated by OM (Rumpel et al., 2002). Below 30 cm depth the microbial community structure and functioning are strongly decreasing and becoming similar to pedological conditions (van Leeuwen et al., 2017) which can also strongly influence radiocarbon age.

The SOC turnover decreases with decreased carbon concentrations as carbon turnover strongly depends on the likelihood of a decomposer particle to meet a substrate particle (Don et al., 2013).

As the ^{14}C age only represents a mixture of the carbon age in the soil sample, it cannot be clearly deduced how much carbon is stored in the soil in the long term. Old carbon indicated by high radiocarbon ages must not necessarily also present on higher quantity of stabilised carbon which is difficult to decompose due to the physical protection or chemical resistant material. High radiocarbon ages can also result from the likelihood that microorganisms (especially in the subsoil) preferentially use fresh, translocated SOC for catabolism, retaining a pool of old (but not stable) carbon in their biomass (Hobley et al., 2017).

More research on stable pools and the use of advanced techniques along the chronosequence can give further information on the OC storage potential and the mechanisms behind long term carbon storage.

4.2. 4 per 1000 and soil organic carbon for food security and climate

The perception of soil organic matter as tool for climate change mitigation and food security is growing. Theoretically, the world's cropland soils could sequester 62 t C in the next 50 to 75 years (0.8–1.2 t ha^{-1} a^{-1}) (Lal, 2016) by restoration of degraded/desertificated soils und by using new technological options such as conservation tillage, use of manures, and compost as per integrated nutrient management and precision farming strategies, conversion of monoculture to complex diverse cropping systems, meadow-based rotations and winter cover crops, and establishing perennial vegetation on contours and steep slopes (Lal, 2003).

A summary of worldwide SOC accumulation rates of agricultural land suggests slightly lower potential accumulation rates of 0.2–0.5 t C ha^{-1} a^{-1} after the adoption of best management practices (Minasny et al., 2017).

A common point to discuss is that many soils show a C saturation where no more storage is possible. Our study shows still an increase of OC stocks in ~500 years old soils. However, this increase is very low with 0.15 t C ha^{-1} a^{-1} at soils with an age of ~500 years and only 0.01 t C ha^{-1} a^{-1} at soils with a maximum deposition age of 17,000 years (Fig. 4). OC accumulation under semi-natural conditions is strongly decreasing due to fast turnover processes in the topsoil in our study region.

Based on the OC stocks (0–40 cm) of the forest and grassland systems (Fig. 3), an equation was derived of the yearly increase. This equation allows determination of the exact year when OC accumulation rates are getting below 4‰ in the Marchfeld (Fig. 5, Table 2). The calculated time span of 59 years of soil formation on fresh river sediments is of rather low importance as the aim of this study was to estimate OC accumulations in soils covering the whole Holocene.

It can also be discussed, that soils of old croplands have a potential to increase their OC content as they have so much lower OC contents compared with soils on forest or grassland systems. However, even a conversion to forests would not allow an annual accumulation of 4‰ C in most croplands for many years.

Different best management practices cause a rapid increase in soil organic carbon. However, this increase is only temporary and only achievable with a high energy input (e.g. high amount of manure input) if the soil status has already reached a carbon saturation. Higher C concentrations increase carbon turnover as the energetic investment for OC decomposition (e.g. biosynthesis of exoenzymes) is lower than the energy gain from mineralization causing a faster decomposition after some time (Don et al., 2013). Long term studies showed that fertilization causes only slow differences in OC concluding that the use of arable soils for carbon sequestration is limited, of low relevance and only depleted soils can temporarily accumulate carbon up to their optimum C content (Körschens et al., 2013).

5. Conclusions

This study showed that accumulation of OC in soils is a very fast process at the beginning of soil development. On forest sites, the OC accumulation slows down from 1.3 t OC ha^{-1} a^{-1} at the beginning of soil development to 0.5 t OC ha^{-1} a^{-1} in soils with a sediment deposition age of ~100 years to only 0.01 t OC ha^{-1} a^{-1}. This shows that after 100 to 350 years the soil reaches a carbon saturation. The radiocarbon determination reveals that dynamics are always very fast in the topsoil.

The fast turnover processes of SOC can be linked to the similar mostly 'modern' and '>modern' radiocarbon age along the chronosequence. In the subsoil different conditions occur compared to the topsoil (less microbial activity, less organic input). Therefore, much older radiocarbon ages were detected in the subsoil (3671 ± 35 BP).

In view of the '4/1000' initiative our results show, that under forest and grassland in the Marchfeld area, soils older than 59 years can only accumulate <4‰ per year. Considering that most soils are older than 60 years, Chernozems in the Marchfeld under current climate cannot contribute in the medium and long-term to the 4/1000 initiative. The study showed that carbon accumulation is strongly limited by the soil development. Even under land use change the saturation of carbon after ~100–350 years strongly limits any increase of OC. Further it must be considered that most carbon in the topsoil is exposed to such high turnover processes that an increase of carbon might only be temporary even under land management.

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Appendix A. Supplementary data

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